

# Tests of Gravity with Gravitational Waves

Miguel Zumalacárregui

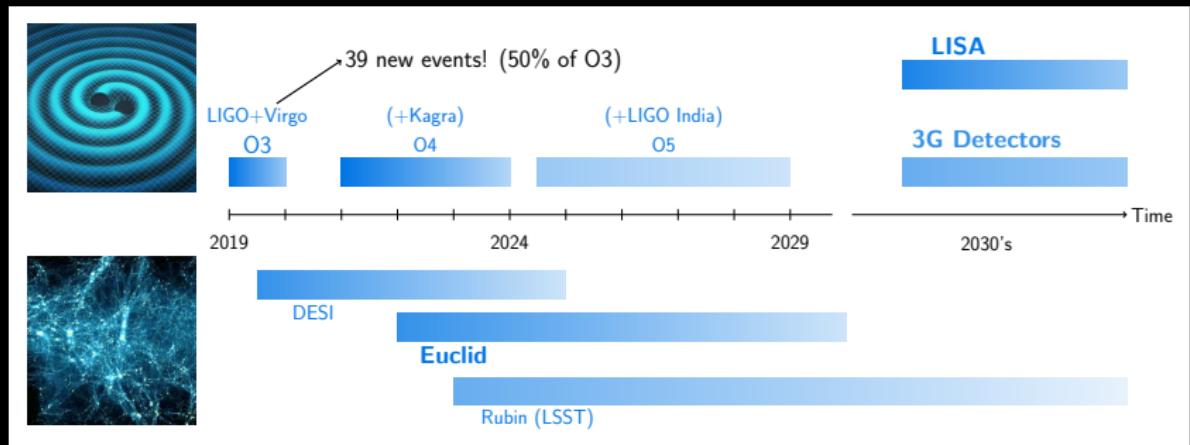


Max Planck Institute for Gravitational Physics  
(Albert Einstein Institute)  
Berkeley Center for Cosmological Physics

December 10<sup>th</sup>, 2020

# Expect Progress (on Old and New Themes) in Cosmology

$\sim 1 \text{ event/week}$

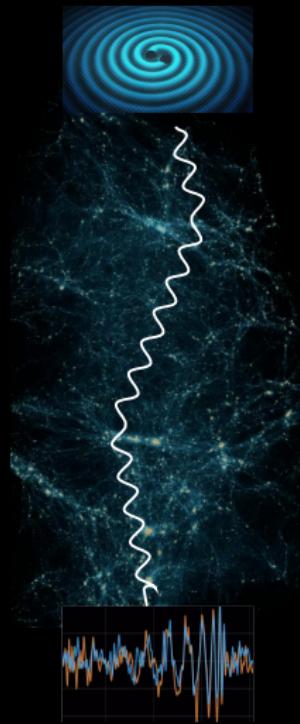


$\sim 10 - 100 \times$  better tests of gravity (Alonso+ '17)

Virtuous circle cosmology & gravitational waves

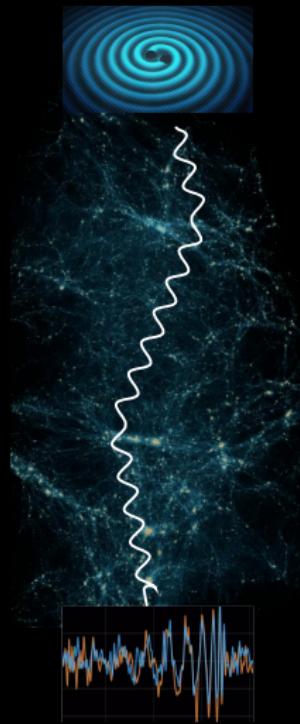
# Outline

- Theories of Gravity
- GW propagation on FRW
  - Speed, Friction
  - Dispersion, Oscillations
- GW lensing
  - Birefringence, Echoes, (Shadows)
- Conclusions



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**gravity**

'gravɪtɪ/

*noun*

1. [Physics]  
the force that attracts a body towards the centre of the earth, or towards any other physical body having mass.
2. extreme importance; seriousness.

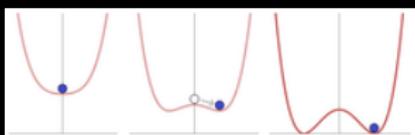
Sources: google (1,2)

# Why modified gravity?

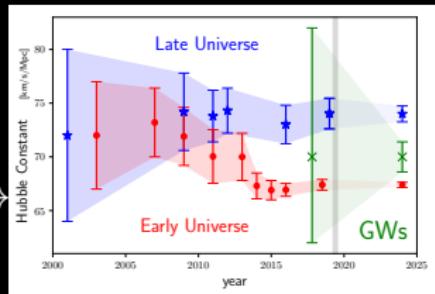
- Interesting theoretical questions:

$\sim 30\%$  of open problems in physics involve gravity

(see [www.wikipedia.org/wiki/List\\_of\\_unsolved\\_problems\\_in\\_physics](http://www.wikipedia.org/wiki/List_of_unsolved_problems_in_physics))



- Alternatives to  $\Lambda$ 
  - Inflation again?  $n_s \neq 1$
  - $\Lambda$ CDM tensions



- Test gravity on all regimes

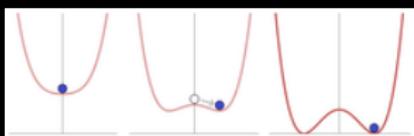
(Ezquiaga & MZ '18, MZ '20)

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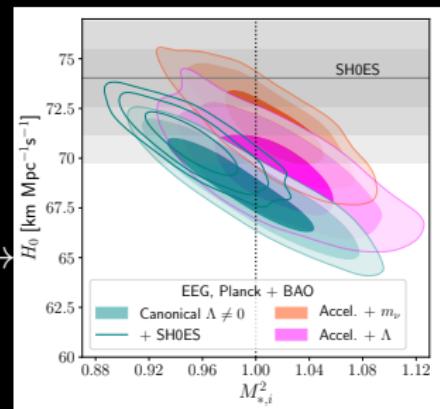
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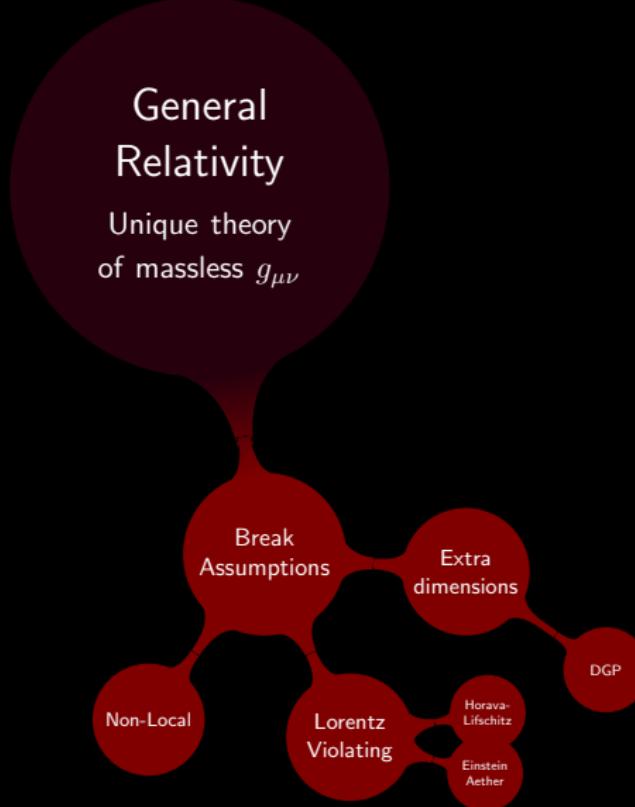


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(Ezquiaga & MZ '18, MZ '20)

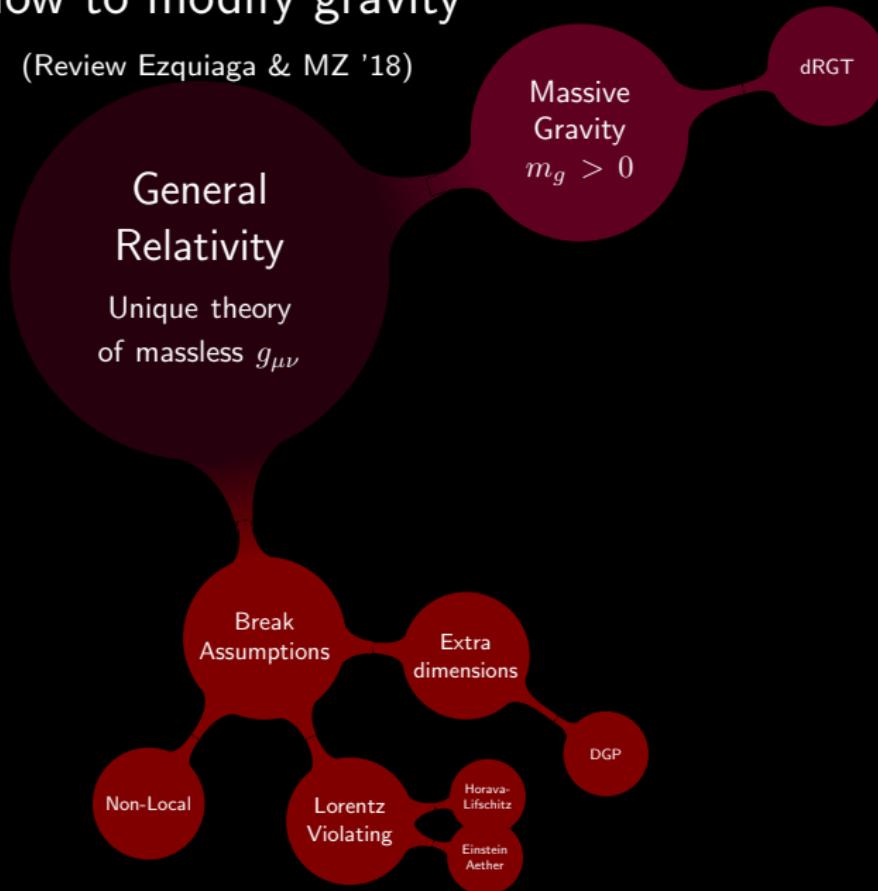
# How to modify gravity

(Review Ezquiaga & MZ '18)



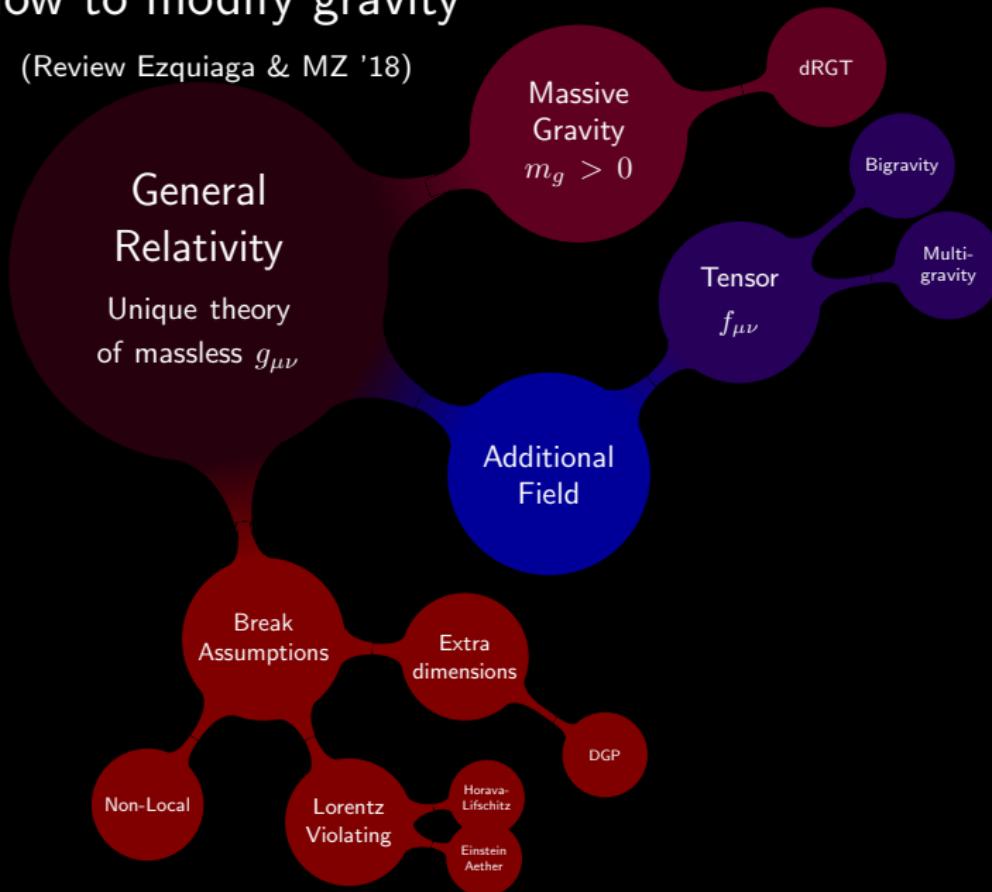
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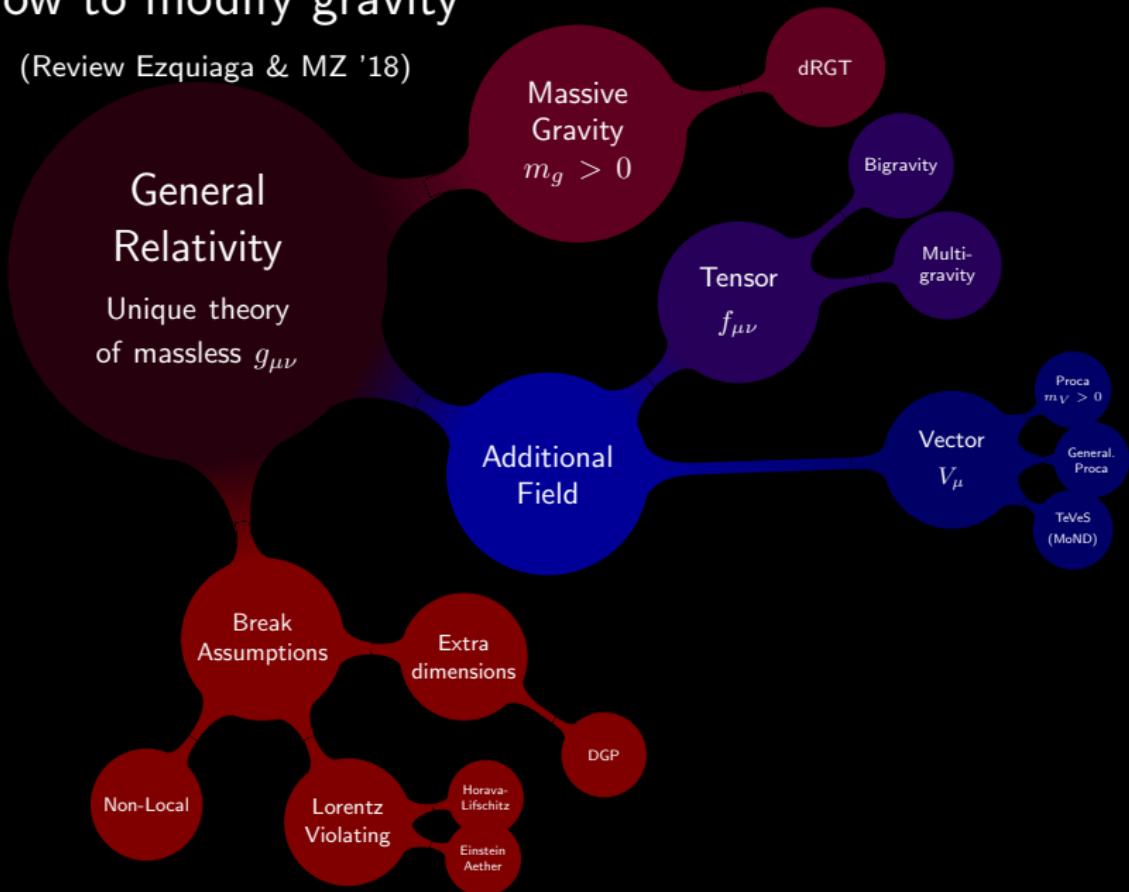
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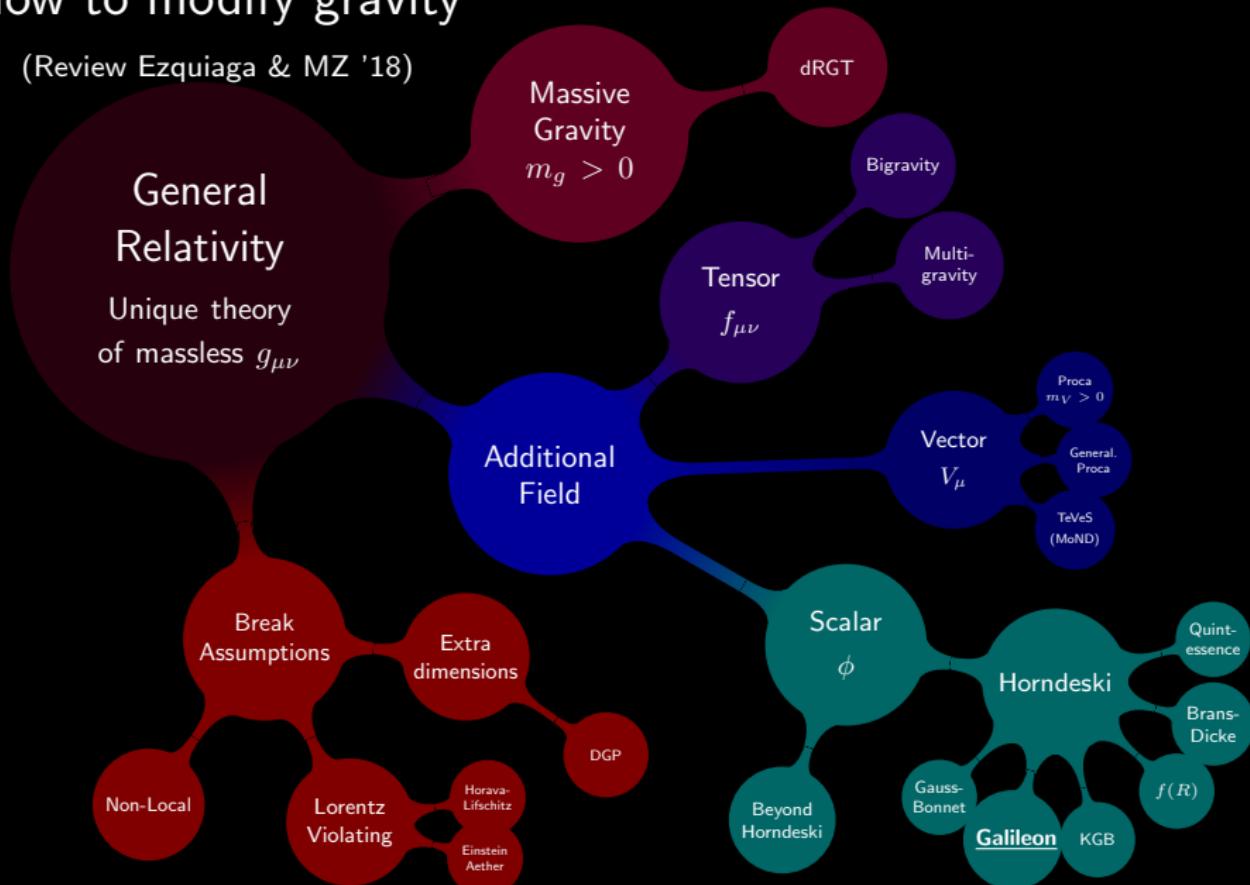
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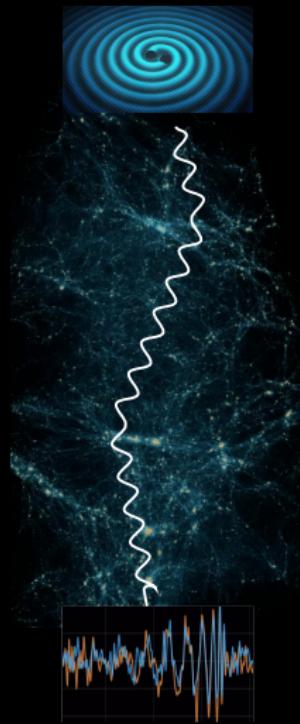
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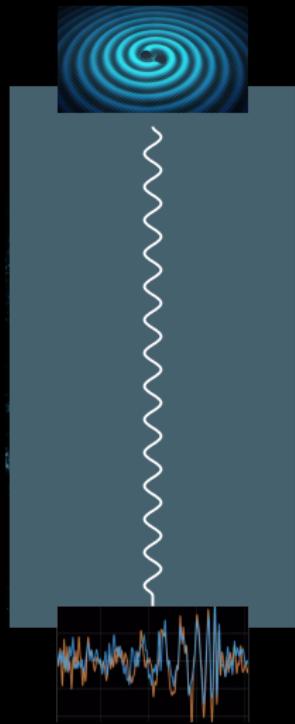
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FRW propagation  $\rightarrow 4 \times$  effects (Nishizawa '17, Ezquiaga & MZ '18)

$$\ddot{h}_{ij} + \underbrace{(1 + \alpha_T)}_{\text{speed}} k^2 h_{ij} + 3H \underbrace{(1 + \alpha_M)}_{\text{damping}} \dot{h}_{ij} + \underbrace{m_g^2}_{\text{dispersion}} h_{ij} = \underbrace{\mu^2 f_{ij}}_{\text{oscillations}}$$

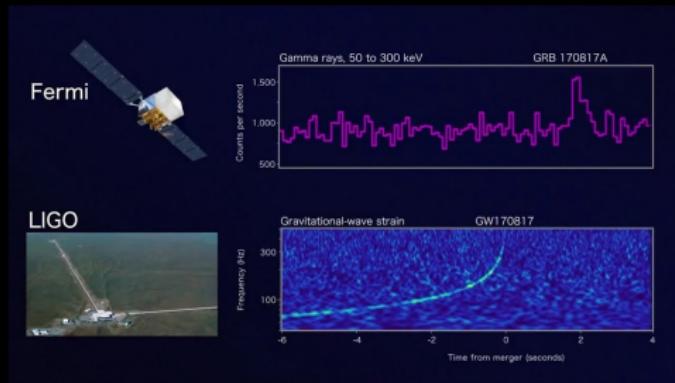
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Plane waves  $\tilde{h}_{ij} = e^{i(\omega t - \vec{k}\vec{x})} = \text{Ampli.} \cdot e^{i\text{phase}}$

	Dispersion $\omega^2$	phase	Ampl.	freq. dep.
Speed	$(1 + \alpha_T) \vec{k}^2$	✓	-	No

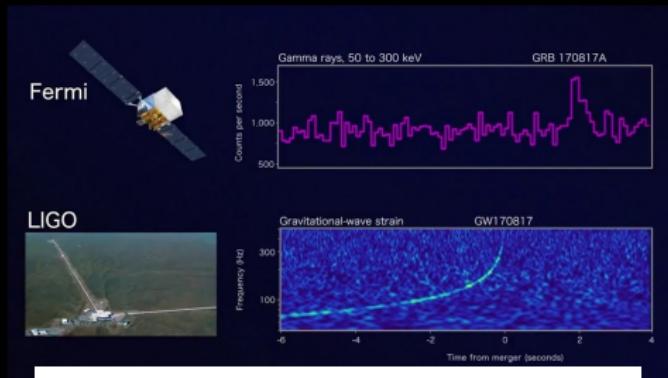
# GW speed: Many theories ruled out



$$|\alpha_T| < \frac{10 \text{ s}}{40 \text{ Mpc}} \approx 10^{-15}$$

(LIGO , Virgo, Fermi, INTEGRAL '17)

# GW speed: Many theories ruled out



[2] arXiv:1710.05901 [pdf, other]

### Dark Energy after GW170817

Jose María Ezquiaga (1 and 2), Miguel Zumalacárregui (2 and 3) ((1) Madrid IFT, (2) UC Berkeley, (3) Comments: 9 pages, 3 figures  
Subjects: Cosmology and Nongalactic Astrophysics (astro-ph.CO); General Relativity and Quantum Cosmology (gr-qc); High Energy Physics - Phenomenology (hep-ph)

[3] arXiv:1710.05893 [pdf, other]

### Implications of the Neutron Star Merger GW170817 for Cosmological Scalar-Tensor

Jeremy Sakstein, Bhuvnesh Jain  
Comments: five pages, two figures  
Subjects: Cosmology and Nongalactic Astrophysics (astro-ph.CO); General Relativity and Quantum Cosmology (gr-qc); High Energy Physics - Phenomenology (hep-ph)

[4] arXiv:1710.05877 [pdf, ps, other]

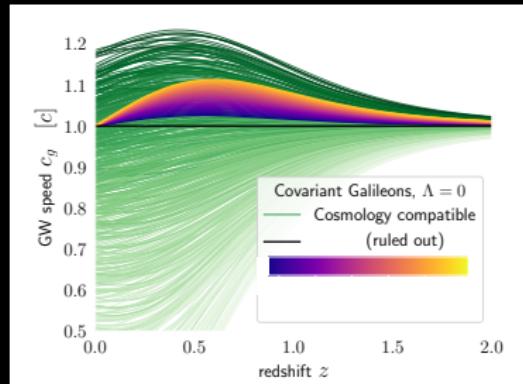
### Dark Energy after GW170817

Paolo Creminelli, Filippo Vernizzi  
Comments: 5 pages  
Subjects: Cosmology and Nongalactic Astrophysics (astro-ph.CO); General Relativity and Quantum Cosmology (gr-qc); High Energy Physics - Phenomenology (hep-ph)

See also Baker+ '17 (Early work Lombriser+,  
Brax+ '15, Bettoni+ '16 · · ·)

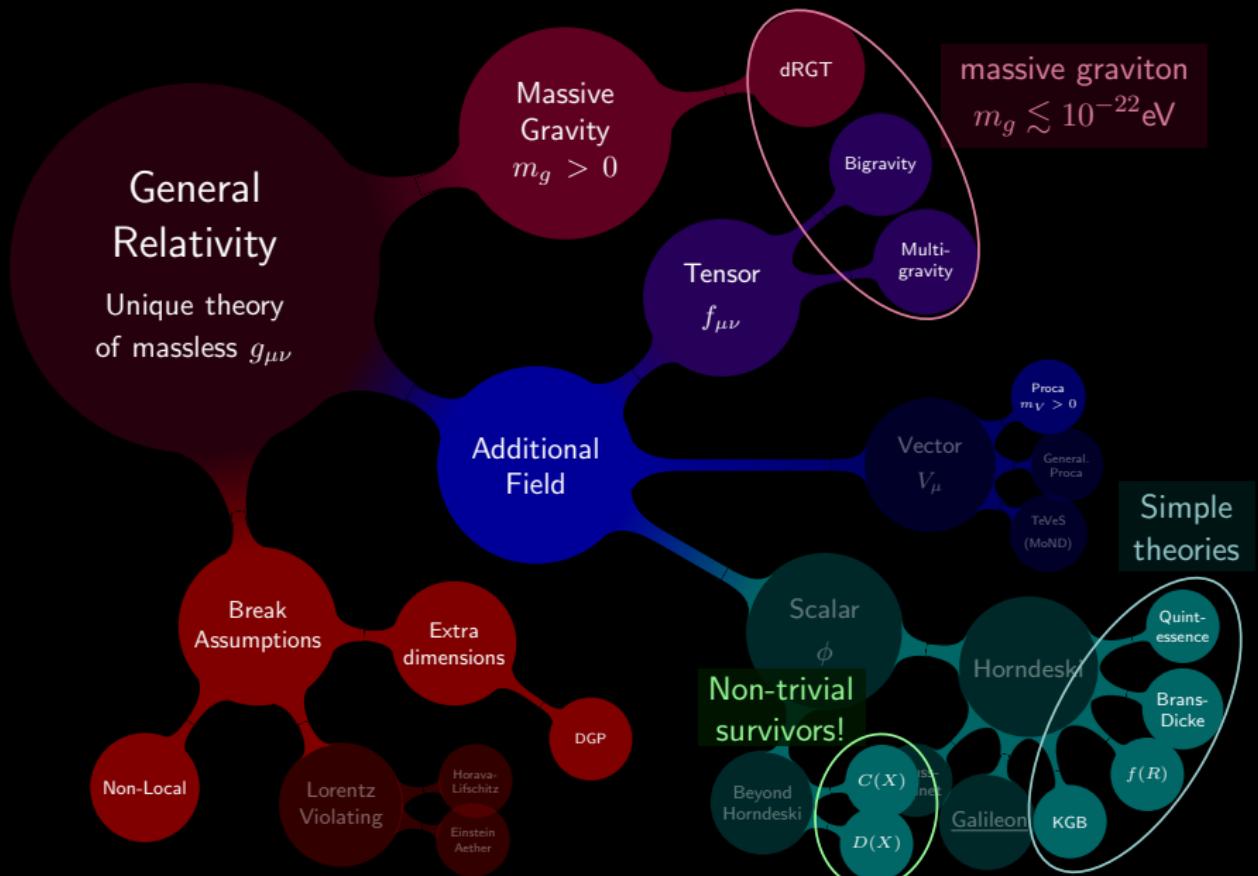
$$|\alpha_T| < \frac{10 \text{ s}}{40 \text{ Mpc}} \approx 10^{-15}$$

(LIGO , Virgo, Fermi, INTEGRAL '17)



# DE after GW170817

(Ezquiaga & MZ PRL '17)



# FRW propagation $\rightarrow 4 \times$ effects (Nishizawa '17, Ezquiaga & MZ '18)

$$\ddot{h}_{ij} + \underbrace{(1 + \alpha_T)}_{\text{speed}} k^2 h_{ij} + 3H \underbrace{(1 + \alpha_M)}_{\text{damping}} \dot{h}_{ij} + \underbrace{m_g^2}_{\text{dispersion}} h_{ij} = \underbrace{\mu^2 f_{ij}}_{\text{oscillations}}$$

Plane waves  $\tilde{h}_{ij} = e^{i(\omega t - \vec{k}\vec{x})} = \text{Ampli.} \cdot e^{i\text{phase}}$

	Dispersion $\omega^2$	phase	Ampl.	freq. dep.
Speed	$(1 + \alpha_T) \vec{k}^2$	✓	-	No
Damping	$+3i\omega H(1 + \alpha_M)$	-	✓	No

# GW damping & decay

(Pardo+18, Belgacem+19, Baker+20...)

$$\ddot{h}_{ij} + \underbrace{(1 + \alpha_T)}_{\text{speed}} k^2 h_{ij} + 3H \boxed{\underbrace{(1 + \alpha_M) \dot{h}_{ij}}_{\text{damping}}} + \underbrace{m_g^2}_{\text{dispersion}} h_{ij} = \underbrace{\mu^2 f_{ij}}_{\text{oscillations}}$$

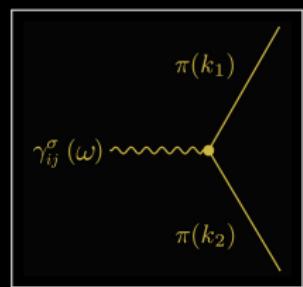
$$\frac{D_L^{\text{GW}}}{D_L^{\text{EM}}} = \exp \left[ -\frac{1}{2} \int_0^z \frac{\alpha_M(z')}{1+z'} dz' \right]$$

★ GW170817:  $|\alpha_M| < \mathcal{O}(10)$  (Lagos+ '19)

★ Screening hides effect (Dalang & Lombriser '19)

★ GW decay into scalar field → beyond Horndeski interactions

(Creminelli+ '18, '19)



# FRW propagation → 4× effects (Nishizawa '17, Ezquiaga & MZ '18)

$$\ddot{h}_{ij} + \underbrace{(1 + \alpha_T)}_{\text{speed}} k^2 h_{ij} + 3H \underbrace{(1 + \alpha_M)}_{\text{damping}} \dot{h}_{ij} + \underbrace{m_g^2}_{\text{dispersion}} h_{ij} = \underbrace{\mu^2 f_{ij}}_{\text{oscillations}}$$

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	Dispersion $\omega^2$	phase	Ampl.	freq. dep.
Speed	$(1 + \alpha_T) \vec{k}^2$	✓	-	No
Damping	$+3i\omega H(1 + \alpha_M)$	-	✓	No
Dispersion	$+m_g^2$	✓	-	Yes

# GW mass/dispersion

(Review: de Rham + '16)

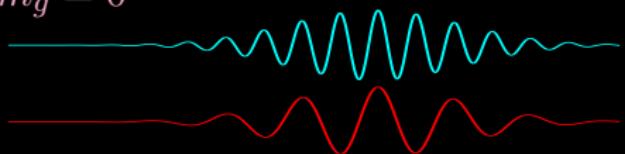
$$\ddot{h}_{ij} + \underbrace{(1 + \alpha_T)}_{\text{speed}} k^2 h_{ij} + 3H \underbrace{(1 + \alpha_M)}_{\text{damping}} \dot{h}_{ij} + \boxed{\underbrace{m_g^2}_{\text{dispersion}} h_{ij}} = \underbrace{\mu^2 f_{ij}}_{\text{oscillations}}$$

$$v_g^2(f) \approx 1 - \frac{m_g^2}{f^2}$$

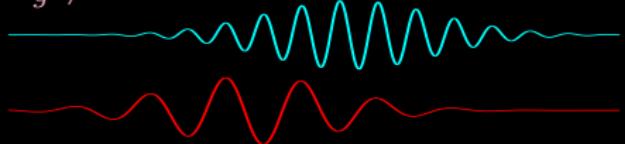
$$m_g \leq 7.7 \cdot 10^{-23} \text{ eV} \quad (\text{LIGO})$$

$$m_g \lesssim 10^{-26} \text{ eV} \quad (\text{LISA})$$

$$m_g = 0$$



$$m_g \neq 0$$



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Speed	$(1 + \alpha_T) \vec{k}^2$	✓	-	No
Damping	$+3i\omega H(1 + \alpha_M)$	-	✓	No
Dispersion	$+m_g^2$	✓	-	Yes
Oscillations	$\omega_1 \neq \omega_2$	✓	(✓)	(Yes)

# GW oscillations

(Max et al '16, Belgacem+ '19, Beltran-Jimenez+ '20)

$$\ddot{h}_{ij} + \underbrace{(1 + \alpha_T)}_{\text{speed}} k^2 h_{ij} + 3H \underbrace{(1 + \alpha_M)}_{\text{damping}} \dot{h}_{ij} + \underbrace{m_g^2}_{\text{dispersion}} h_{ij} = \underbrace{\mu^2 f_{ij}}_{\text{oscillations}}$$

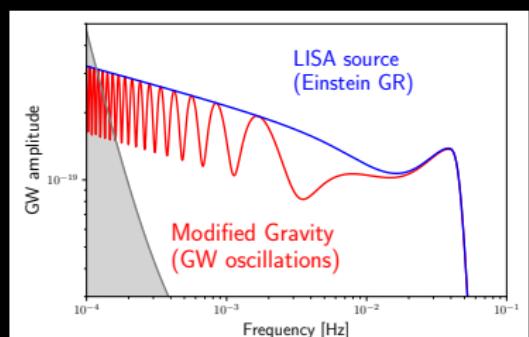
$\sim$  neutrino flavour oscillations

$$\frac{\text{missing } h_{ij}}{\text{produced } h_{ij}} \propto f \left( \frac{\mu^2}{m_g^2} \right) \cos \left( \frac{m_g^2 L}{4f} \right)$$

$$m_g^2 \lesssim 10^{-22} \text{ eV} \quad (\text{LIGO})$$

$$m_g^2 \lesssim 10^{-25} \text{ eV} \quad (\text{LISA std. sirens})$$

Cosmo-CMB predictions (Cusin+, Lagos+, Amendola+ 15)



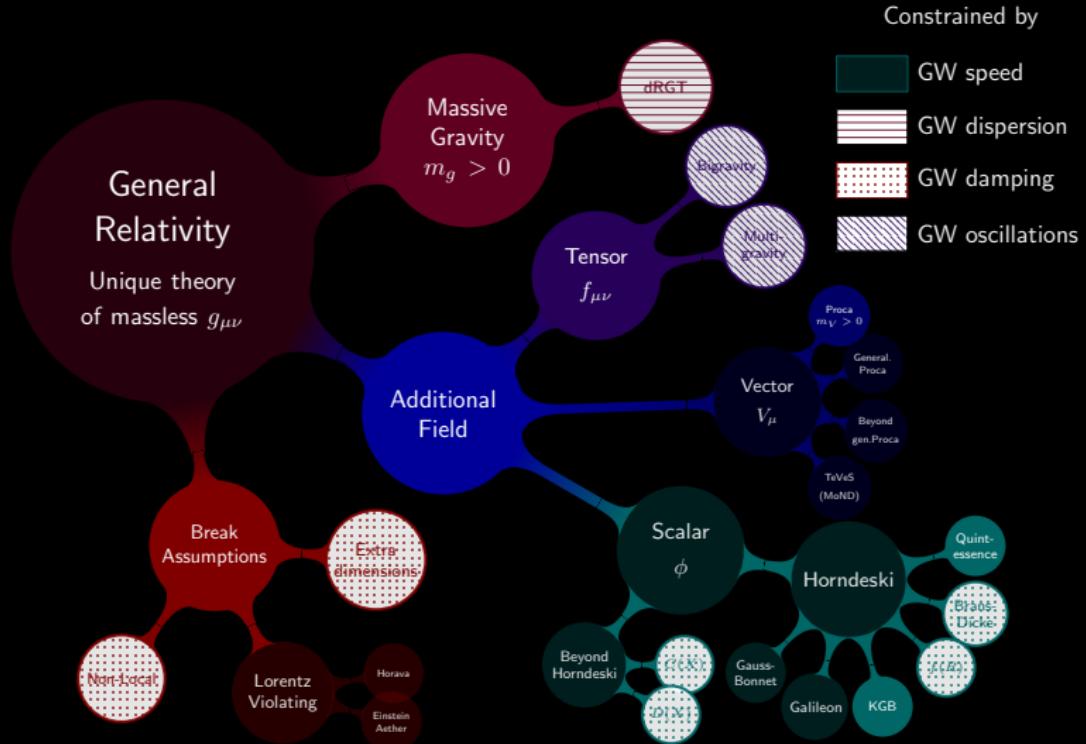
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	Dispersion $\omega^2$	phase	Ampl.	freq. dep.	bounds
Speed	$(1 + \alpha_T) \vec{k}^2$	✓	-	No	$ \alpha_T  \lesssim 10^{-15}$
Damping	$+3i\omega H(1 + \alpha_M)$	-	✓	No	$ \alpha_M  < \mathcal{O}(10)$
Dispersion	$+m_g^2$	✓	-	Yes	$m_g \lesssim 10^{-22} \text{eV}$
Oscillations	$\omega_1 \neq \omega_2$	✓	(✓)	(Yes)	$m_g, \mu \lesssim 10^{-22} \text{eV}$

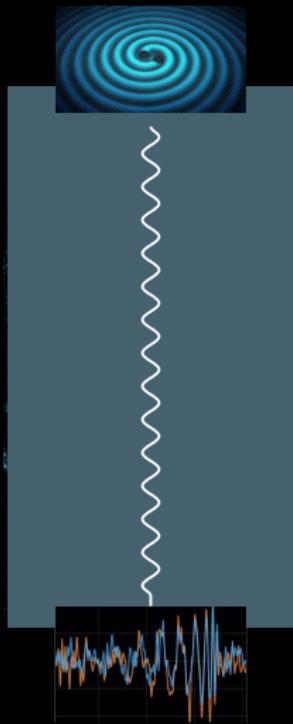
+ GW-induced instabilities (Creminelli+20), additional polarizations, ...

# FRW propagation $\rightarrow 4 \times$ effects (Nishizawa '17, Ezquiaga & MZ '18)



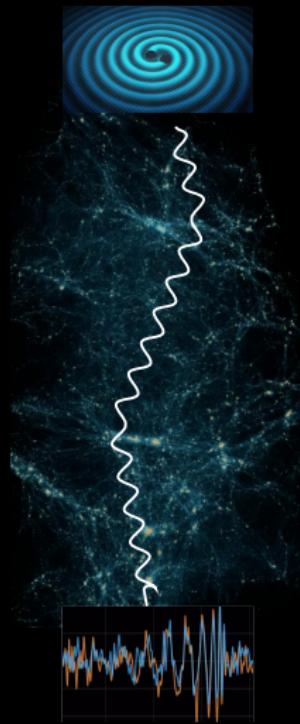
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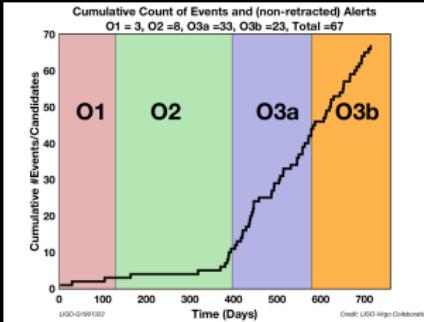


# Why GW lensing beyond GR?

- Gravitational lensing → robust test of GR, DE, DM...
- FRW well understood

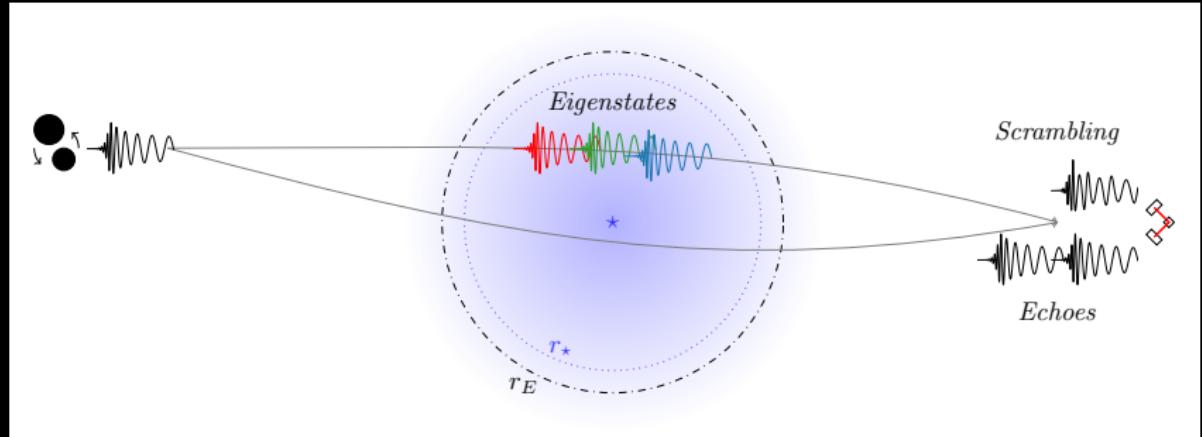
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- Many more GW events → deviations from average universe



# New Results at leading order

(See also Dalang+ 20)



- GWs ( $h_+, h_\times$ ) + new d.o.f.  $\leftrightarrow$  propagation eigenstates
- Waveform effects (no EM counterpart needed)
- Potentially more constraining than GW170817

(Ezquiaga & MZ 20)

# Equations at leading order (Ezquiaga & MZ '20)

- Define  $V = (g_{\mu\nu}, \phi)$
- Perturb  $V_i = \bar{V}_i + \delta V_i$ ,
- Expand  $\Delta V_i = H_i \left( A_i^{(0)} + \epsilon A_i^{(1)} + \dots \right) e^{i\theta/\epsilon}$

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- Fix gauge, solve constraints  $3 \times$  propagating d.o.f.  $\dots$   
$$h^i{}_i \propto \bar{\phi}^i \bar{\phi}^j h_{ij}^{TT} + (\bar{\phi}^\perp)_i{}^i \varphi \quad (\text{GW shadows})$$

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- Leading order  $\epsilon^{-2}$  in  $k_\mu \equiv \theta_{,\mu}$

$$\begin{pmatrix} \square_h & 0 & M_\phi \square_m \\ 0 & \square_h & 0 \\ M_\phi \square_m & 0 & \square_s \end{pmatrix} \begin{pmatrix} h_+ \\ h_\times \\ \varphi \end{pmatrix} = 0$$

- Propagation speeds  $\square_I \propto k_0^2 - c_I^2(\hat{k}) |\vec{k}|^2$ ,
- Mixing coefficients  $M_{ij}$

# Propagation Eigenstates (e.g. neutrino flavor mixing)

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- Diagonalize:

- Pure metric:  $H_1 \propto h_\times$ ,  $c_1^2 = c_h^2$

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- Diagonalize:

- Pure metric:  $H_1 \propto h_\times$ ,  $c_1^2 = c_h^2$

- Mostly metric:  $H_2 \propto h_+ + M_\phi \frac{\Delta c_{mh}^2}{\Delta c_{hs}^2} \varphi + \dots$   
 $c_2^2 = c_h^2 + M_\phi^2 \frac{(\Delta c_{hm}^2)^2}{\Delta c_{hs}^2} + \dots$

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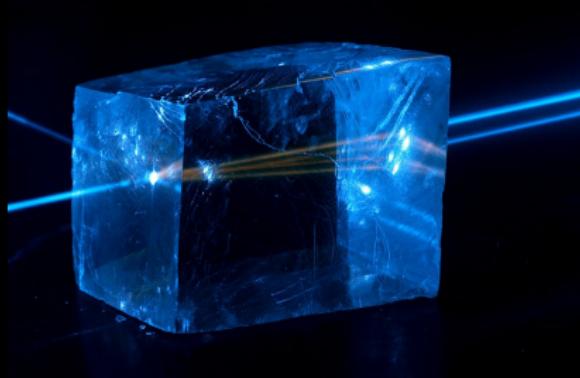
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- Diagonalize:
  - Pure metric:  $H_1 \propto h_\times$ ,  $c_1^2 = c_h^2$
  - Mostly metric:  $H_2 \propto h_+ + M_\phi \frac{\Delta c_{mh}^2}{\Delta c_{hs}^2} \varphi + \dots$   
 $c_2^2 = c_h^2 + M_\phi^2 \frac{(\Delta c_{hm}^2)^2}{\Delta c_{hs}^2} + \dots$
  - Mostly scalar:  $H_3 \sim \varphi + \mathcal{O}(M_\phi) h_+$ ,  $c_3 = c_s + \dots$

# Birefringence

Eigenstate speed depends on *position* ( $\vec{x}$ ) and *direction* ( $\hat{k}$ )

★ 4× signals, speeds

- EM  $\rightarrow c_0$
- Pure metric  $H_1 \rightarrow c_1$
- Mostly-metric  $H_2 \rightarrow c_2$
- Mostly-scalar  $H_3 \rightarrow c_3$



# Birefringence

Eigenstate speed depends on *position* ( $\vec{x}$ ) and *direction* ( $\hat{k}$ )

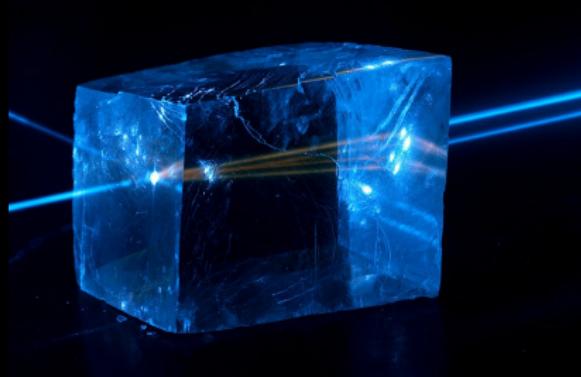
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★ 3× time delays:

- $\Delta t_{01}$  Multi-messenger delay
- $\Delta t_{12}$  Polarization delay
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★ 3× relative deflections  $\lesssim \alpha_{\text{GR}}$



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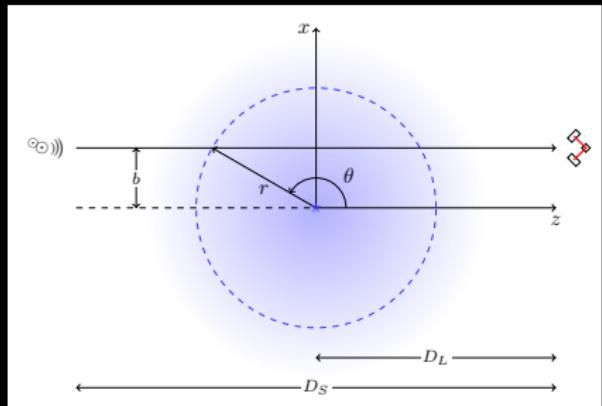
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$$\Delta t_{ij} \approx \underbrace{\int \left( c_i^{-1} - c_j^{-1} \right) dl}_{\text{Shapiro}} + \Delta t_{ij}^{\text{geo}}$$

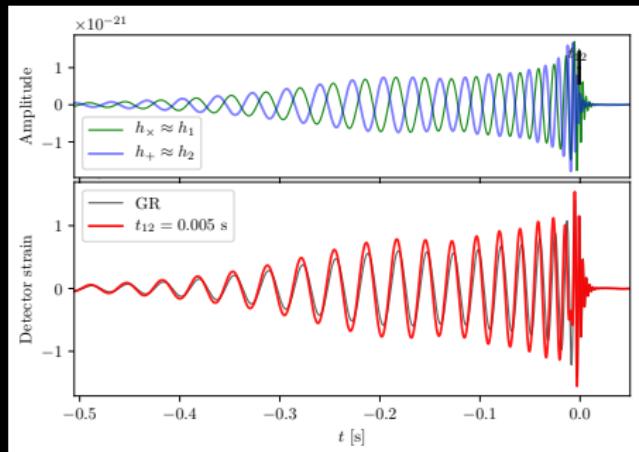
# Polarization Time Delays $\Delta t_{12}$

## Assumptions

- Circularly polarized signal
- $\varphi \sim 0$ , amplitude  $H_i \sim h_i$

## Two Regimes

- “Scrambling”  
 $\sigma_t < \Delta t_{12} < t_{\text{signal}}$



$$(\mathcal{A}^+ = -0.38, \mathcal{A}^\times = 0.71)$$

- Clear(-ish) signal, no need for EM counterpart!
- Degeneracies with binary parameters?

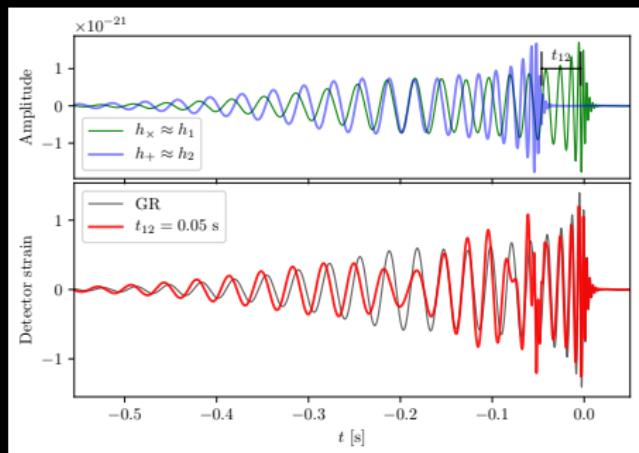
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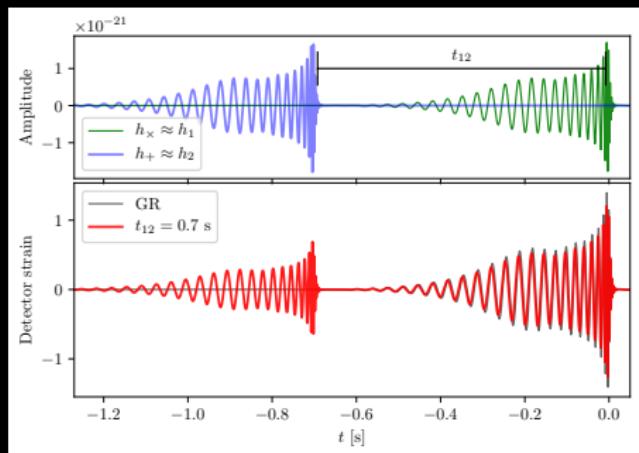
# Polarization Time Delays $\Delta t_{12}$

## Assumptions

- Circularly polarized signal
- $\varphi \sim 0$ , amplitude  $H_i \sim h_i$

## Two Regimes

- “Scrambling”  
 $\sigma_t < \Delta t_{12} < t_{\text{signal}}$
- “Echoes”  $\Delta t_{12} > t_{\text{signal}}$ 
  - polarized signals
  - might get lost
  - $N$  echoes →  $h \sim 1/N$



$$(\mathcal{A}^+ = -0.38, \mathcal{A}^\times = 0.71)$$

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# Example: Horndeski's theory

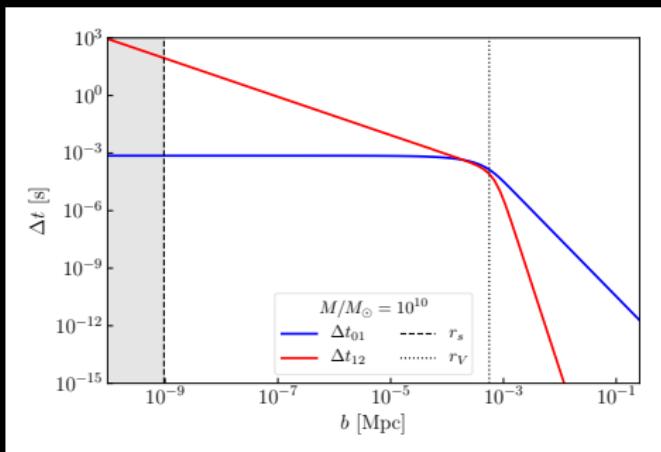
$$\mathcal{L} \supset \frac{M_p^2}{2} \left( 1 + p_{4\phi} \phi - \frac{(\partial\phi)^2}{\Lambda_4^2} \right) R - 2 \frac{(\partial\phi)^2}{\Lambda_4^2} \left( (\square\phi)^2 - \phi_{\mu\nu}\phi^{\mu\nu} \right)$$

GW170817:

$$c_g/c - 1 \sim p_{4\phi}^2 \frac{H_0^2}{\Lambda_4^2} \lesssim 10^{-15}$$

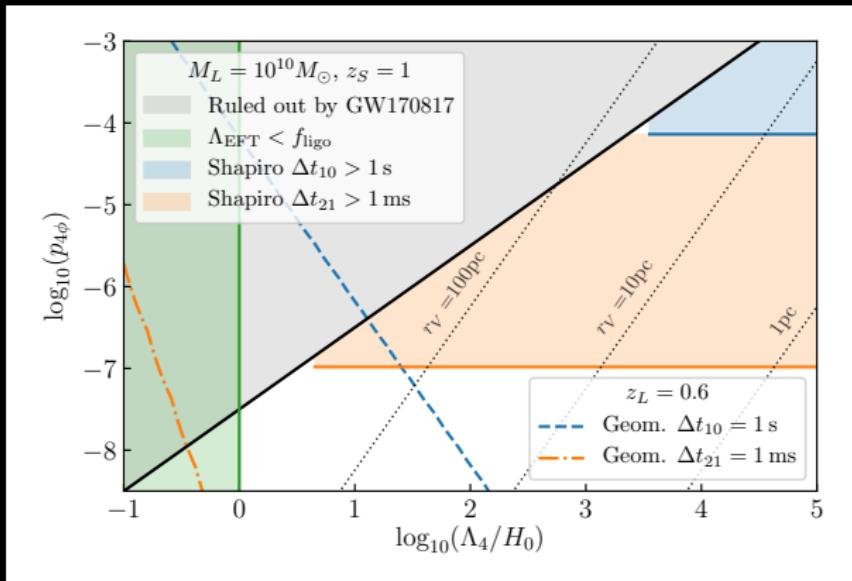
Point mass  $10^{10} M_\odot$ :

- Delay large  $b \lesssim r_V$
- Polarization delay large!



$$\Lambda_4 \sim H_0, p_{4\phi} \sim 10^{-8}$$

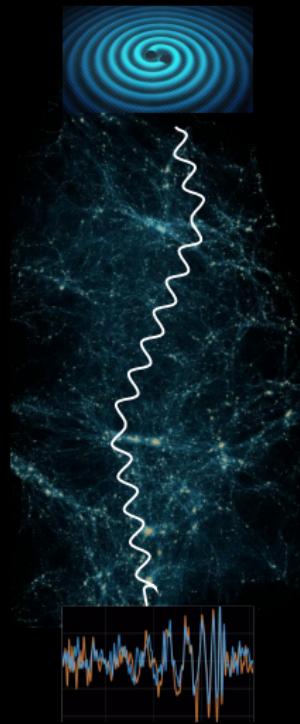
# Potential constraints



- Potential to go beyond GW170817!
- Need heavy + dense lens (GW190521 if in SMBH/AGN)

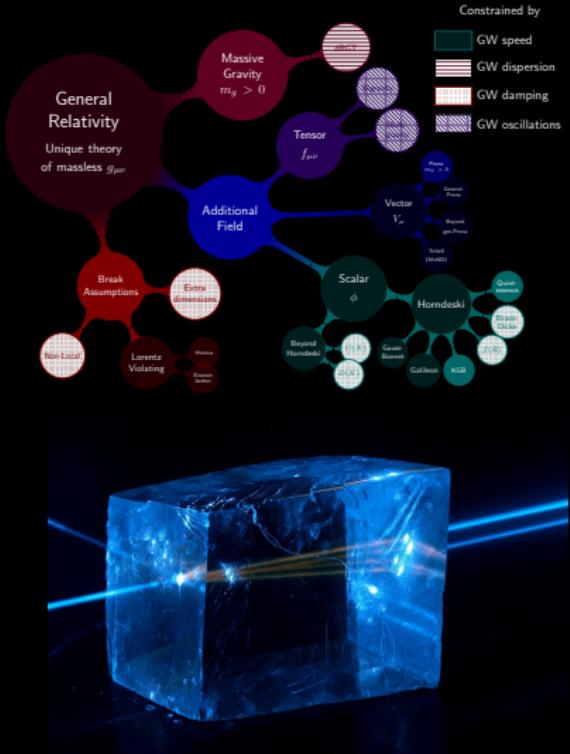
# Outline

- Theories of Gravity
- GW propagation on FRW
  - Speed, Friction
  - Dispersion, Oscillations
- GW lensing
  - Birefringence, Echoes, (Shadows)
- Conclusions



## Conclusions

- $\exists$  good reasons to study/test gravity
  - GW propagation on FRW  
 $\sim 4\times$  tests only!
  - $c_g = c \rightarrow$  construct/select theories
  - GW lensing new effects
    - $3\times$  time delays
    - no need for EM counterpart
    - strong bounds possible!
  - GW-lensing To Do:
    - Statistics, searches...
    - Lower order, other theories...
  - Probes weak in  $\Lambda$ CDM critical beyond



**gravity**

'graviti/

*noun*

1. [Physics]

the force that attracts a body towards the centre of the earth, or towards any other physical body having mass.

2. extreme importance; seriousness.

3. in the context of fermenting alcoholic beverages, refers to the specific gravity, or relative density compared to water, of the wort or must at various stages in the fermentation.

$$\boxed{\frac{d}{dt} \text{gravity} \propto \text{alcohol \%}}$$

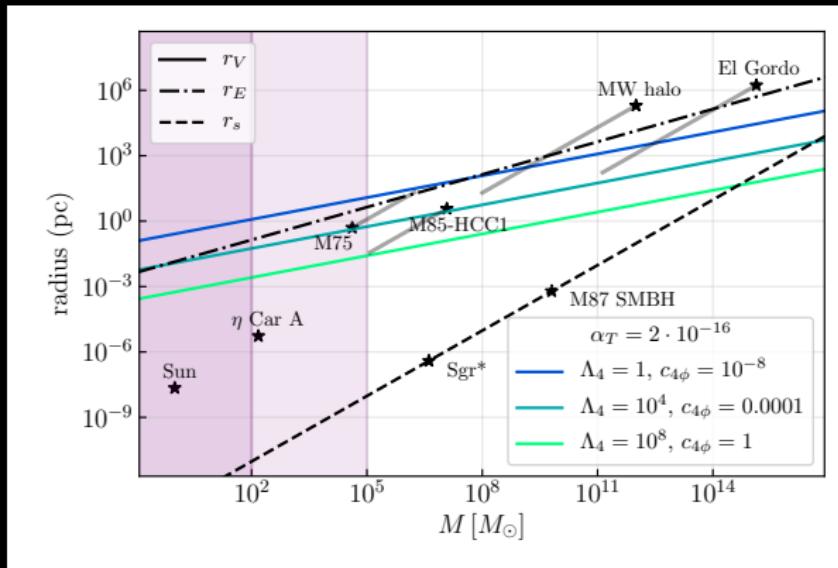
⇒ ∃ at least a useful “test” of gravity!



Sources: google (1,2), wikipedia (3)

## Backup Slides

# Lenses



- Low mass lenses  $\rightarrow$  short-wave expansion breaks
- Central region of extended lenses?

# Conditions for variable $c_g$

(Bettoni, Ezquiaga, Hinterbichler & MZ '16)

Operationally:  $\ddot{h}_{ij} + c_g^2 \vec{\nabla}^2 h_{ij} + \dots = 0$

GW effective metric - any background,  $k^2 \gg |R_{\mu\nu}|$

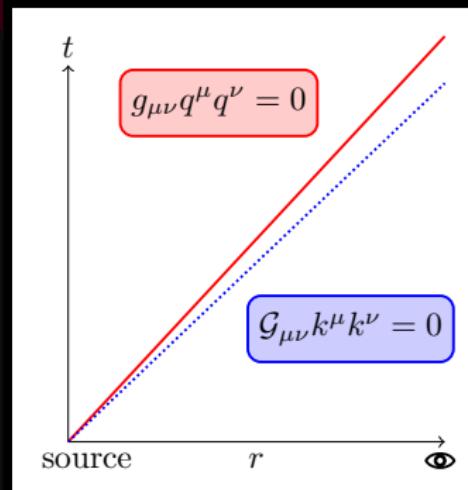
$$\text{GW eq} \propto \underbrace{(\mathcal{C}\square + \mathcal{D}_{\mu\nu}\partial^\mu\partial^\nu)}_{\mathcal{G}_{\mu\nu}\partial^\mu\partial^\nu} h_{ij}$$

1) Non-trivial  $\phi(x) \rightarrow \mathcal{D}_{\mu\nu} \propto \partial_\mu\phi\partial_\nu\phi \dots$

Cosmology  $\rightarrow \dot{\phi} \sim H_0$

2)  $\phi$ -derivatives couple to Riemann Curvature

$$R_{\mu\alpha\nu\beta} \rightarrow \underline{\partial_\mu\partial_\nu} h_{\alpha\beta}^{\text{TT}} \quad (R_{\mu\nu} \rightarrow \square h_{\mu\nu}^{\text{TT}})$$

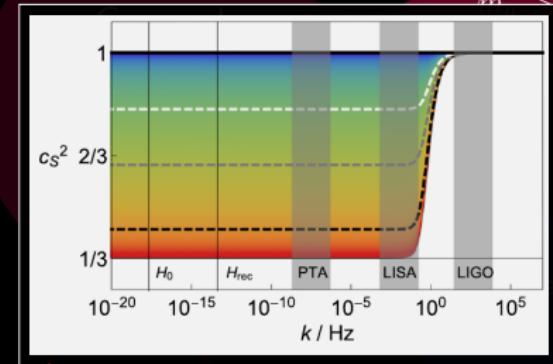


(1,2)  $\Rightarrow \phi$  changes the effective medium in which GWs propagate.

(2)  $\Rightarrow$  binary classification of theories

# DE after GW170817

(Ezquiaga & MZ PRL '17)



⚠ DE EFT cutoff  $\lesssim 100\text{Hz}$

(de Rham & Melville '18)

Assumptions

Extra dimensions

Non-Local

Lorentz Violating

Horava-Lifschitz  
Einstein Aether

DGP

Non-trivial survivors!

$C(X)$

$D(X)$

massive graviton  
 $m_g \lesssim 10^{-22}\text{eV}$

dRGT

Bigravity

Multi-gravity

Tensor

$f_{\mu\nu}$

Vector

$V_\mu$

Proca  
 $m_V > 0$

General Proca

TeVeS  
(MoND)

Simple theories

Quint-essence

Brans-Dicke

$f(R)$

Horndeski

KGB

Galileon